Distributed Sensing for Marine Electrical System Monitoring and Protection Applications

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Synopsis

In this paper, technology developed at the University of Strathclyde which has resulted in the commercialisation of distributed point sensors for electrical and mechanical parameters will be described. While primarily targeted at terrestrial power system applications to date, this technology has significant potential for realising novel and effective monitoring and protection solutions for marine electrical systems. In the paper, the technology and its capabilities will be reviewed, and a number of potential applications will be described and discussed briefly. Many of these applications can assist in reducing the levels of risk associated with marine electrical systems, through delivering comprehensive monitoring and protection functions that benefit from the distributed nature of the measurement system. The measurement system will be outlined and it will be shown how it consists of a central interrogator that uses optical fibre to collect several measurements from a distributed, and, importantly, completely passive, array of sensors that are connected along the length of the fibre, which can be up to 100 km in length (clearly adequate for any marine applications). Finally, the paper will describe a number of distributed monitoring and protection applications in marine electrical systems that can be facilitated by the distributed measurement system.

Keywords: Measurements, sensing, electrical systems, monitoring, protection.

1. Introduction

A major global trend in marine systems is towards more and all-electric propulsion systems [1], whereby electrical power is distributed electrically to ship propulsion systems and other loads to improve the efficiency, control, flexibility and costs of the system. However, the increasing reliance on an electrical system, the use of novel zonal architectures systems employing DC, the advent of batteries and other forms of storage, and research into technologies such as superconducting cables and machines, all increase the importance of possessing adequate knowledge of system health and in responding to faults and other desirable conditions in a timely and safe manner.

In recent years there have been a number of instances of "black ships" [2] or complete loss of electrical power within vessels, many of which have been caused by electrical faults on the vessel's power system that may not have been dealt with correctly by the electrical protection systems. It is proposed that a holistic approach to vessel electrical and plant monitoring and protection is required. From a techno-economic perspective, the best unified sensing solution will provide high-quality real-time data from a densely-structured power system, while reducing instrumentation and overall monitoring and protection system costs. By unifying conventionally-disparate systems for measurement of electrical current, voltage, and thermal/environmental parameters, photonic sensing has the potential to provide streamlined, integrated instrumentation able to provide enhanced visibility and discrimination of the status of a complex electrical system, and this presents opportunities to develop and apply enhanced, and in some cases novel, monitoring and protection functions.

Present techniques (primarily disparate single-point measurement systems with dedicated communication channels) can lead to protection systems that may not be fit for purpose under all scenarios; for example, they may exhibit slow response times in detecting and isolating faults in certain circumstances. The distributed sensing system described in this paper offers opportunities to overcome such problems.

2. Overview of the distributed sensing technology

Modern marine system often incorporate optical fibre networks throughout the structure as standard for communications and control purposes. The distributed sensing system reported in this paper could utilise these pre-installed fibres as sensors that can measure all parameters that operators and platform management systems require for electrical system control, monitoring, and protection functions - providing a way both to meet instrumentation demands at lower cost, and to enable the enhancement and unification of marine electrical instrumentation. Alternatively, if the distributed sensing system were to be installed at the vessel construction or fitting-out stages, then the cost of including dedicated fibre for the sensing system would be marginal.

The distributed sensing system incorporates an interrogator unit with distributed sensors based on Fibre Bragg Gratings (GBGs) placed at various locations within the fibre. Since this technology utilises the fibre directly, it is completely passive, requiring no power supply or communications equipment at each sensor location. The sensor fibre, with sensors embedded in it, can effectively be viewed as a single distributed analogue sensor, and can deliver the required data in a highly efficient and secure manner. In order to measure voltage and current, FBG sensors can be combined with piezoelectric transducers – single or multiple layered – to conveniently adapt to the input voltage range [3]. The piezoelectric transducer imparts strain upon an FBG in direct proportion to input voltage (Fig. 1a). By combining a multi-layered transducer with a current transformer, an integrated current sensor can be constructed (Fig. 1b). Modern piezostacks, as shown in Fig. 1c, offer exceptional sensitivity and are suitable to be combined with Rogowski coils to benefit from their non-saturating nature.

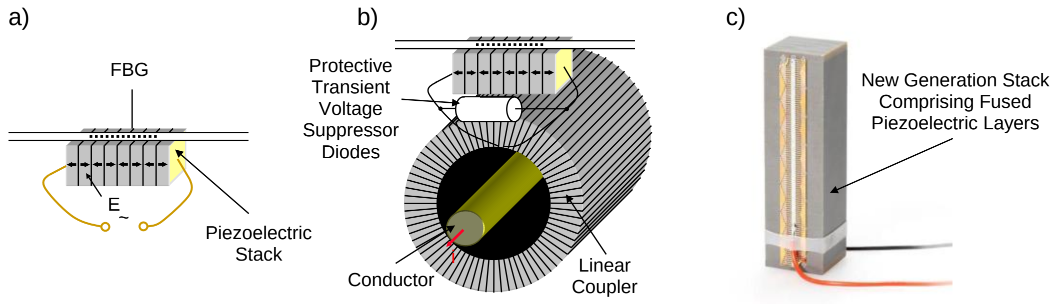

Figure 1. (a) – optical voltage transducer comprising fibre Bragg grating (FBG) and piezoelectric stack; (b) – hybrid current sensor employing linear coupler; (c) – new generation high-sensitivity piezostack.

The sensing system is practically deployed as shown in Fig. 2(a) below, with a single continuous fibre running between sensor locations. In the diagram shown, the fibre runs alongside the power system cable between nodes, with sensors shown at each line end; although in theory sensors could be placed at any location along the lines. Fig. 2(b) shows an early concept CAD model for a combined voltage and current measurement device using piezoelectric FBG sensors for installation on outdoor power networks.

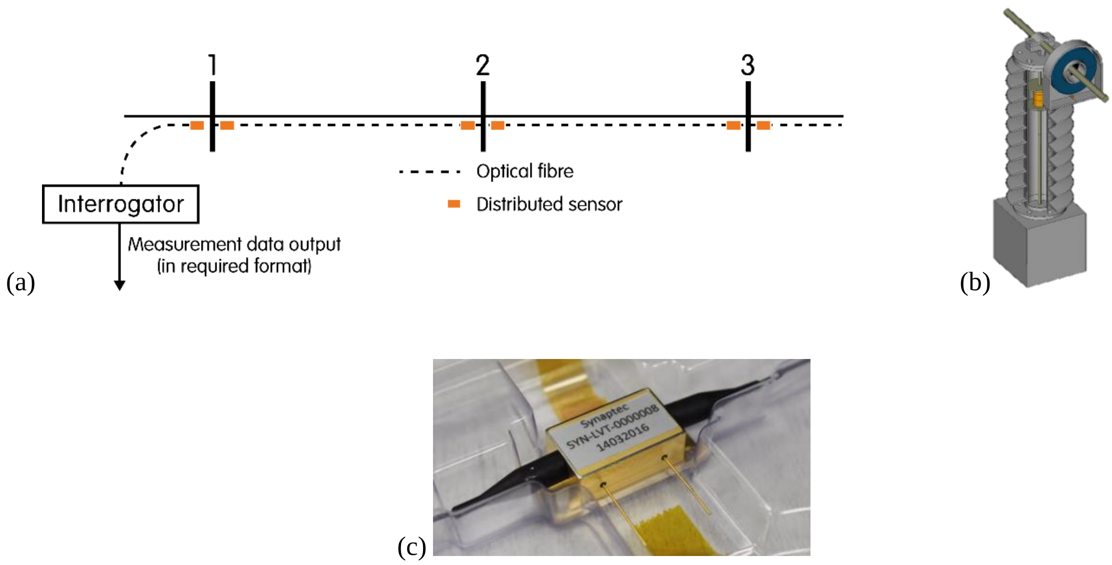

Figure 2. (a) Illustration of centralised multi-parameter distributed electrical sensing, (b) computer model of packaged outdoor voltage and current measurement device for terrestrial applications (c) an inline sensor (with fibre entering and leaving the sensor).

Further details of the sensing system are shown in Figure 3, where it is clear how each FBG sensor, when interrogated with a broadband light source, reflects at a particular element of the spectrum. The wavelength of the reflected light is modulated in response to the stain (or temperature) exerted on the fibre sensor, and the interrogator can ascertain the measurement parameter, e.g. current as derived through the sensor arrangement shown in Figure 1(b), through knowledge each individual FBG sensor's reflective characteristics and by converting the amplitude-modulated reflections into the measurement parameter at the sensor location using appropriate algorithms.

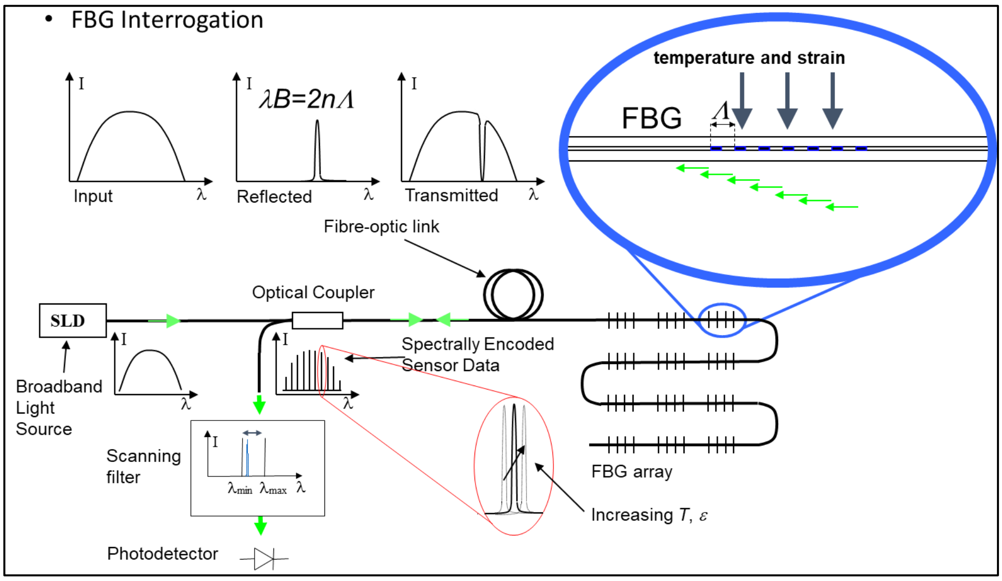

Figure 3. Main components of the sensing system

The all-optical technique eliminates the need for digital communications between measurement points, removes bandwidth bottlenecks and facilitating an efficient and robust unified sensor network for all electrical (and mechanical) parameters.

3. Potential applications

A typical marine electrical system architecture is illustrated below in Figure 4:

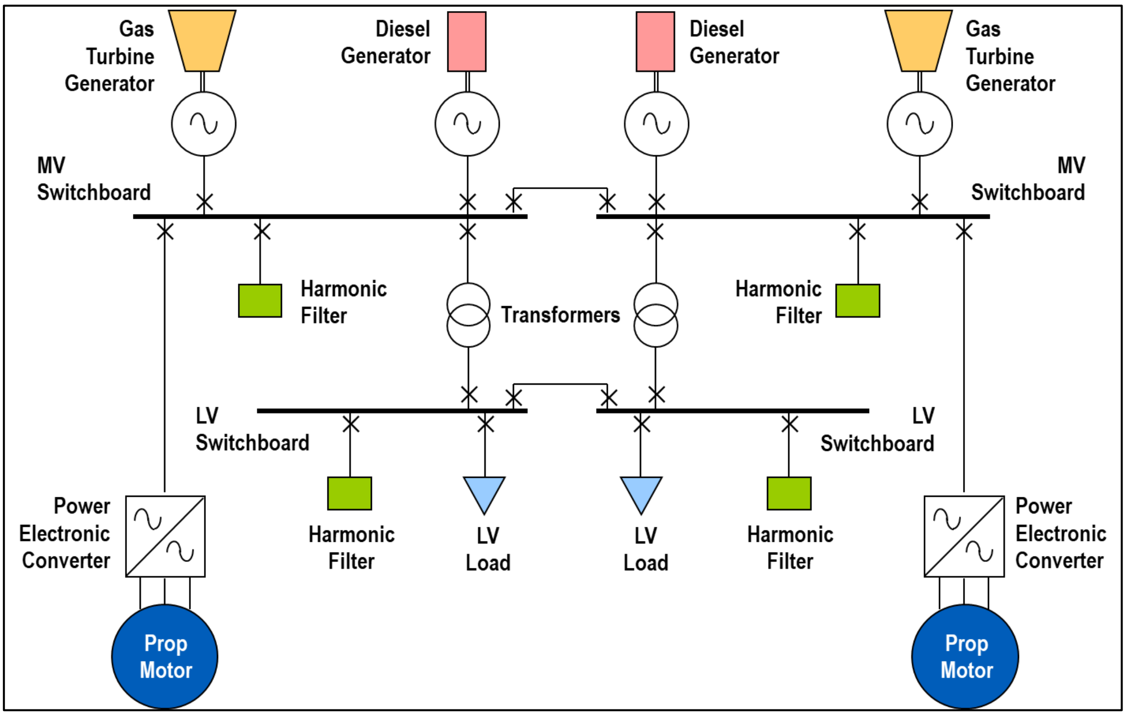

Figure 4: Typical Integrated Full Electric Propulsion System Architecture

If, for example, sensors were placed at the locations shown below in Figure 5, then a number of monitoring and protection functions could be readily implemented. These functions, how they would operate, and the potential benefits that they could offer, are described briefly below the figure.

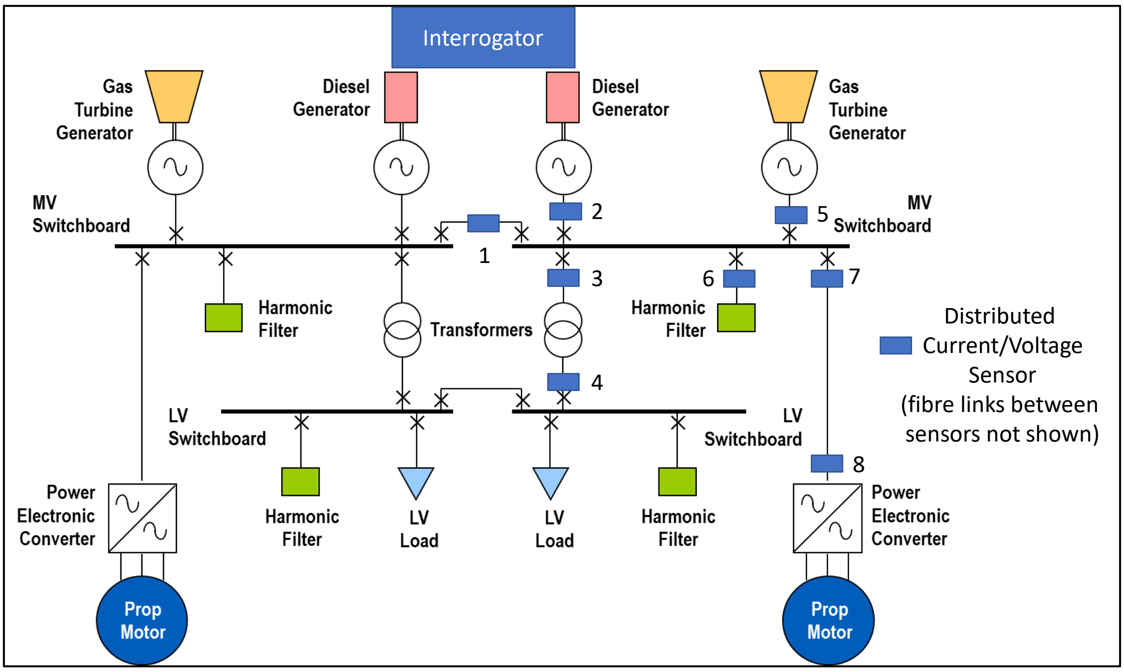

Figure 5: System Architecture with Distributed Sensors

3.1. *Multi-zone differential main protection*

With reference to Figure 5, sensors 1, 2, 3, 5, 6 and 7 could be interrogated to provide a differential protection function for the busbar using the vector sum or simple directional comparison of all currents entering and leaving the bus. The outputs from sensors 3 and 4, and 7 and 8, could be used to protect the transformer and the line to the converter respectively, with a relatively simple differential algorithm based on comparisons of magnitude and/or phase of the currents in each phase. This would enable fast, accurate and discriminative protection of large areas of the system to be achieved from a single location. Further sensors distributed throughout the LV system (not shown in the figure) could be interrogated to provide either overcurrent or differential protection of the various lines and other items of equipment throughout the system.

A major benefit of this arrangement, when compared with overcurrent systems that may be used to protect cable sections in particular, is that the system could provide very fast and discriminative protection, and would effectively be “settings free”, other than the configuration of relatively simple bias and threshold settings associated with the differential protection function. This is in contrast to overcurrent-based schemes, which typically require relatively complex settings to be calculated to ensure that correct operation will occur under all circumstances, and that backup is provided in the event of failure of a protection system or circuit breaker through the appropriate time and current grading characteristics of the overall scheme.

A further advantage compared to overcurrent schemes is that differential systems are insensitive to fault levels (which could change drastically depending on the generation plant connected to the marine system at any particular time) and to fault resistance, which, in overcurrent schemes may affect the speed of operation, and the provision of backup in an effective manner. As mentioned in earlier sections of the paper, the distributed sensing system is passive and does not require any dedicated communications hardware at line terminals or multiple protection relays, so the economics and complexity of the system are favourable.

The sensing system, in its present form, can output IEC 61850-9-2 sampled value data, which is the non-vendor specific industry standard, and is in the process of being trialled in the field at a transmission substation as part of a major Ofgem (the GB electricity and gas regulator) funded innovation project led by SP Energy Networks, known as FITNESS[1].

3.2. *Wide-area backup protection*

In general, using comparisons of zone-boundary currents, and logic similar to the main protection function outlined above, backup protection could be provided relatively simply. If, after a pre-determined time delay during which “main” circuit breaker tripping should have been executed, faults and differential currents are still detected, then tripping signals to the appropriate adjacent zone circuit breaker(s) would be issued to effect isolation of the short circuit.

For example, with reference to Figure 5, if there was a fault on the transformer circuit bounded by sensors 3 and 4, and, after the time during which the circuit breaker at sensor 3 should have opened, current was still deemed to be flowing into the fault through sensor 3, then, with an appropriate algorithm, the circuit breakers at sensors 1, 2 and 5 could be instructed to open, thereby clearing the fault via backup operations. The algorithms and logic to effect such functionality are relatively simple.

3.3. *Fault location*

The availability of synchronised and high-resolution measurements of voltage and current from throughout the electrical system offers capabilities to locate faults with great accuracy. The short distances involved in marine electrical systems may be challenging, but investigation of the use of established algorithms such as multi-ended impedance and Takagi methods [4], adapted and improved to cater for the ability to have multiple measurements available as input, may be prudent. At the very least, using the distributed measurements, as for protection functions, offers the capability to discriminate and identify the faulted item(s) of equipment with great certainty using differential/direction comparison algorithms.

3.4. *Impedance measurement and anomaly detection*

One relatively novel application that may be enabled through the use of distributed sensors is to measure the impedance between points in the system, e.g. of a section of cable, of a transformer, etc. This could be achieved through monitoring the current entering and leaving the equipment and calculating the voltage drop between the points; clearly this would require to account for transformer ratios if the plant monitored were a power transformer. Compensating for temperature and other parameters that may influence impedance may be required, but any

[1] https://www.spenergynetworks.co.uk/pages/fitness.aspx (retrieved 27/10/17)

material change in the measured impedance could be indicative of a developing problem (e.g. insulation degradation, high resistance arcing or heating within the equipment) and could be used as an input to plant condition monitoring functions and/or to alert operators and maintenance personnel to any potential problems while they remain in the incipient stage.

3.5. Other monitoring functions

System monitoring functions, based upon measurements of voltage, current and possibly temperature and vibration, from different locations, could be used for a variety of system monitoring functions. For example, to monitor real and reactive power flows, to estimate the state of the system accurately, to detect power quality issues (e.g. total harmonic distortion levels, flicker, voltage dips, etc.), to establish real-time ratings of equipment through online measurement of temperature in conjunction with power flows, to detect system splitting/islanding, etc.

4. Conclusions

This paper has described how distributed sensing of voltages and currents (and possibly other parameters such as temperature and vibration), when made available at a single point, may be used for a multitude of monitoring and protection applications on marine vessels. This could assist in reducing various risks, enhancing the response to electrical system faults, and improving the visibility and knowledge of electrical system and individual asset performance and condition.

All of these functions could potentially contribute to an increase in vessel reliability, availability and safety. While not mentioned in the main body of the paper, the reliability of the sensor system itself is clearly a major consideration. This could be enhanced by introducing redundancy in the form of duplicate sensors, duplicate interrogators, interrogating the sensors from both “ends” of the fibre, etc. It should be noted that the sensing system, while novel, is based on long-established technologies such as FBGs and piezoelectric materials, which have been used in many applications and have been proved to be extremely reliable [5].

While the technology developed is presently focussed on terrestrial power systems and subsea cables, as it is demonstrated comprehensively in those application domains and matures, the applicability to marine electrical systems will be explored further through development and demonstration projects.

5. References

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